Accretion Disks in Evolved Cataclysmic Variables

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Abstract

We explore conditions and structure of accretion disks in short-period Cataclysmic Variables (CVs), which have evolved beyond the period minimum. We show that accretion discs in systems with extreme mass ratios grow up to the size of corresponding Roche lobe and are relatively cool. In contrast, the viscosity and temperature in spiral arms formed as a result of a 2:1 resonance are higher and their contribution plays an increasingly important role. We model such discs and generate light curves which successfully simulate the observed double-humped light curves of SDSS1238, SDSS0804, SDSS1610 and V 455 And in quiescence.

1. Introduction

According to population models, there should be a significant number of systems near the period minimum [1]. The period distribution of CVs, which include new systems discovered in the Sloan Digital Sky survey (SDSS), confirms the prediction about a accumulation of CV systems close to the orbital period minimum in the range 80—90min [2]. After reaching the period minimum the CVs should evolve back toward longer periods and form a so-called bounce-back or post-period minimum systems. The age of the Galaxy is old enough for significant fraction of the current short-period CV population to have evolved past the orbital period minimum. As the objects evolve further, their luminosity is expected to decrease and their orbital periods may become larger than the period minimum and have an extremely low mass-ratio. The SDSS helped to reveal a number of objects which can be classified as evolved beyond the period minimum and expectations are high that many more bounce-back objects can be identified among faint SDSS CVs. In this report, we discuss possible candidates for post-period minimum systems and their observational characteristics. The origin of double-humped light curves is also discussed as a result of a model of a large cool accretion disk with spiral arms.

2. The sample

Figure 1 illustrates the current concepts of evolution of CVs at the turning point and displays positions of bounce back system candidates on the mass-transfer rate and mass-ratio to the orbital period diagrams. Table 1 lists the available parameters of the post-period minimum candidates (shown within a box in Fig.1, according to [3]). All systems presented in Table 1 show WZ Sge-type spectral characteristics in the optical range, i.e. a mildly blue continuum with relatively weak (compared to ordinary DNe) Balmer emission lines from the accretion disk surrounded by broad absorptions formed in the atmosphere of WD. Four objects (V455 And, AL Com, SDSS0804 and EG Cnc) produced WZ Sge-type superoutbursts in the near past. Estimates of system parameters show the presence of

Table 1. Parameters of WZ Sge and of bounce back candidates.

NN/Object	P_{orb} (days)	V (mag)	q	M_1 ($M_\odot$)	M_2 ($M_\odot$)	T_{eff}^{WD} (K)	i (^{o})	LC[1]
1. WZ Sge	0.0567	~ 15	0.092	0.85	0.078	13500	77	+s
2. GW Lib*	0.0533	19.1	0.060	0.84	0.05		11	
3. V455 And*	0.0563	16.5	0.060s		>M9	11500	83	+q
4. AL Com*	0.0567	19.1	0.060			16300		+q
5. SDSS1035	0.057	18.7	0.055e	0.94	0.05	10100	83	
6. SDSS1238	0.056	17.8	0.05	~ 1.0	0.05	12000	$\sim$70	+q
7. SDSS0804*	0.059	17.8	0.05s	~ 0.9	0.045	13000	$\sim$ 70	+q
8. EG Cnc*	0.060	18.8	0.035s			12300		+s
9. RX1050-14	0.062	17.6	<0.055v			13000	<65	
10. GD552	0.0713	16.6	<0.052v		<0.08	10900	<60	
11. RE1255	0.083	19.0	<0.064v	>0.9	<0.08	12000	< 5	-
12. SDSS1610**	0.0582	19.0						+q

[1] light curve (LC) features: "+" LC shows a double-hump during the orbital period; "s" - during super-outburst; "q" - during quiescence; "-" absent of double-humps in LC.
* - objects which demonstrate WZ Sge-type super-outburst.
** The mass ratio of SDSS1610 is not known, however the objects shows similar observational characteristics to selected candidates and the double-humped light curve too.

relatively cool ($T_{eff} \approx 12000 \pm 1000$K), massive white dwarf ($M_1 \sim 0.9 M_\odot$) and an extremely low value of mass ratio $q \leq 0.06$, which assumes a Jupiter-size brown dwarf as a secondary. High inclination systems frequently exhibit light curves featuring double humps during super-outbursts and in quiescence. Some new phenomena were discovered in bounce-back candidates not seen anywhere else. One is the long 3.5h spectroscopic period not related to the orbital one in V455 And [4], secondly there are the "brightenings" permanently observed in SDSS1238 and occasionally seen in SDSS0804 before it went through super-outburst in March, 2006 [5]. Finally, there are "mini-outbursts" observed in SDSS0804 [6] about one year after the super-outburst.

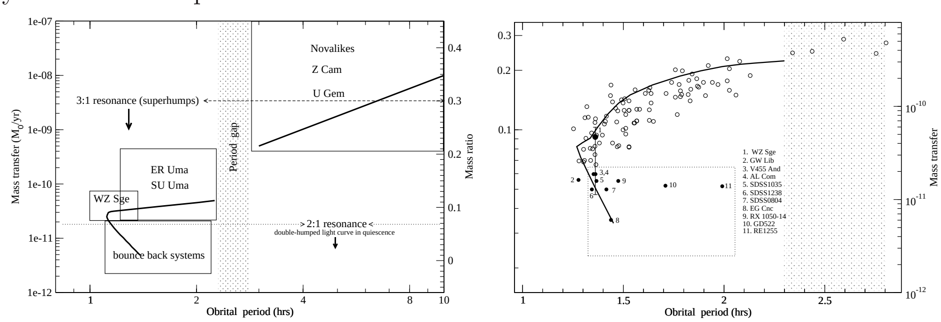

Fig. 1. Left panel) The location of bounce-back systems among other CVs: Right panel) Plot of the mass ratio and the mass transfer rate vs the orbital period. The best bounce back candidates are enclosed in the box.

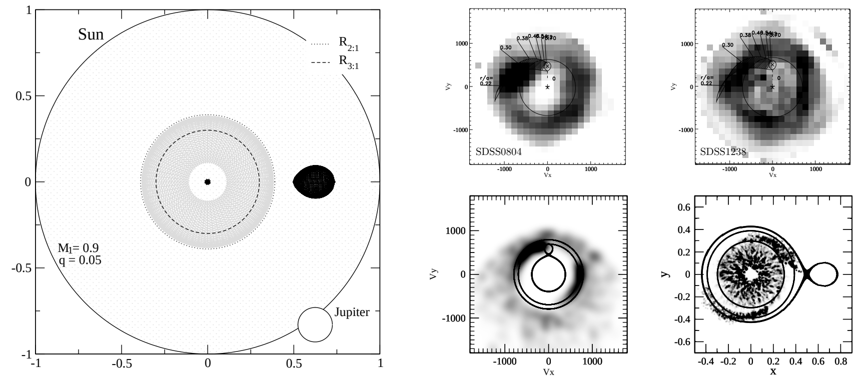

Fig. 2. Left panel) The size of bounce-back system and its component in solar radii. The 2:1 and 3:1 radiuses are shown. Right panel) The Doppler tomograms of SDSS0804 and SDSS1238 (top) and their simulation (bottom).

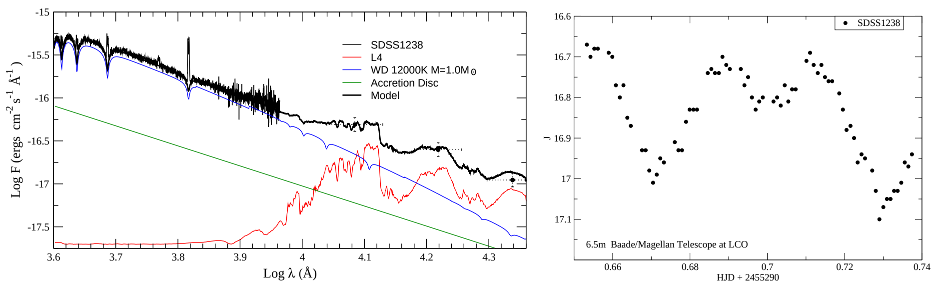

Fig. 3. Left panel) The spectral energy distribution of SDSS1238 and the result of its SED model fit[7]. Right panel) The J band light curve of SDSS 1238.

3. The accretion disk structure.

The accretion disk structure of bounce-back candidates is analyzed here based on our spectral and IR photometric observations of SDSS1238 and SDSS0804 in quiescence. The conditions of the disk are inferred from Doppler tomography maps displaying internal structure on one hand, and on the other from estimates of disk contribution in a system in which both stellar components are clearly visible. Doppler maps of SDSS0804 and SDSS1238 constructed using H_α emission line are shown in Fig.2. There is a bright spot at the expected place where the stream of matter from the secondary collides with the accretion disk, but it overlaps with a much larger and prolonged structure, too large to be part of the spot. Another extended bright region of similar size can be seen at velocity coordinates ($V_x \approx 700\ km/s$, $V_y \approx 0\ km/s$) as well as a less bright structure at $V_x \approx -200\ km/s$, $V_y \approx -800\ km/s$. Similar Doppler maps were obtained during WZ Sge super-outburst in 2001 ([8], [9]) and in quiescence for the bounce-back candidate SDSS 1035[10] and were interpreted as evidence of spiral waves in the disk. The formation of a spiral structure in an accretion disk of a close binary system was predicted by Lin & Papaloizou (1979)[11] and explored further by various authors. Sawada et al. (1986) demonstrated from high resolution numerical calculations that spirals will always form in accretion disks under tidal forces from the secondary[12]. These authors actually used q = 1 in their models but observationally, such spirals were detected in a number of systems only

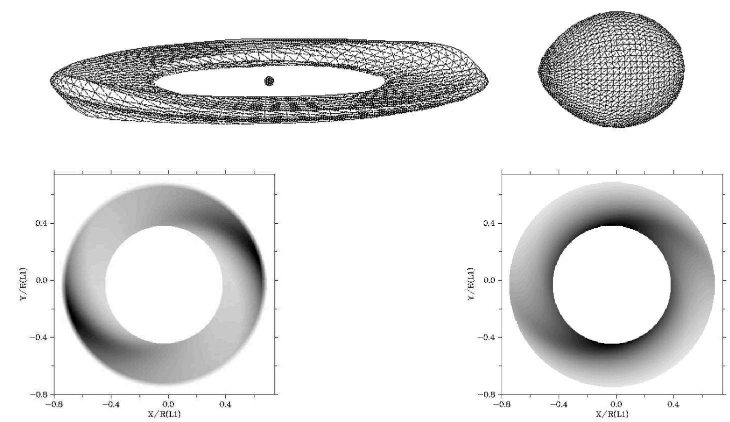

Fig. 4. Top panel: Model configuration of a bounce-back system. Bottom; Left panel) The z-coordinate structure of the accretion disk. Right panel) The disk temperature distribution in the model.

during outbursts of dwarf novae. Careful examination of quiescent disks of the same systems did not reveal any spiral structures in longer period DNe. Steeghs & Stehle (1999) argued that little evidence of spiral arms in the emission lines is expected in systems with low values of viscosity[13]. On the other hand, spiral arms related to 2:1 resonance can be found in systems with extremely low mass ratio $q < 0.1$[11]. The bounce-back systems and others related to them, the WZ Sge stars, are examples of such objects and they are believed to have low viscosity disks. The long outburst recurrence time in WZ Sge systems is probably explained by a very low viscosity in their accretion disks, yet spiral arms can be observed permanently in quiescent bounce-back systems in which, on one side there is a massive WD which gained mass during a long accretion history, and on the side there is a late-type brown dwarf, giving a mass ratio of < 0.06. WZ Sge itself shows double-humped light curve in super-outburst only. Fig. 2,(bottom, right) depicts a synthetic Doppler map constructed from a accretion disk model that is shown on the bottom right panel. The artificial Doppler map reproduces the observed map in a case when there is a brightness excess within the spiral arms. Most of the disk particles are on periodic orbits, which are most favorable from the point-of-view of viscosity. However, the resonance dispatches some particles onto aperiodic orbits creating viscosity perturbations, which will create heat excess. The mechanism is not well established, but it is natural to assume that in these regions there will be excess emission. The spiral arms become prominent in highly evolved systems as the result of contrast, the rest of the accretion disk seems to contribute little to the continuum and is probably mostly optically thin. The visibility of both stellar components is good evidence of distinctly insignificant contribution of the accretion disk to the total optical-IR flux of the system. The J-band light curve and the optical-infrared spectral energy distribution (SED) of SDSS1238 fitted by the three component model (WD, a brown dwarf, and standard $F_\lambda \sim \lambda^{-7/3}$ accretion disk)[7] are shown in Fig.3. The model predicts very small contribution of the disk to the optical flux of the system. The main uncertainty of the model is the slope of the accretion disk continuum. The J-band light curve of SDSS 1238 corresponds to the expected ellipsoidal shape of the secondary with a temperature gradient between the shaded side of the secondary and the face on WD side and

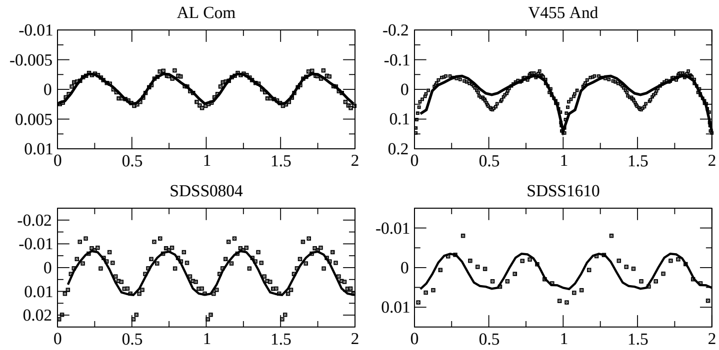

Fig. 5. The light curves of AL Com, V455 And, SDSS0804 and SDSS1610 folded with their orbital periods are shown by square points. The solid line is the light curve obtained from our model for each system.

also supports a low contribution of the accretion disk in IR fluxes.

The shape of the standard spectrum ($F_\lambda \sim \lambda^{-7/3}$) of the accretion disk is based on the blackbody approximation of a disk element intensity and $T_{eff}(r) \approx T_*(r/R_1)^{-3/4}$ relation for the radial temperature structure of a steady state accretion disk[14]. However, the black body accretion disk (optically thick) with a size reaching the radius of 2:1 resonance will dominate over the radiation of the system in the optical range in hot disks or in the IR in low temperature disks at practically any inclination of the system. Therefore, the standard accretion disk model is not in agreement with the structure of accretion disks in bounce-back systems.

What do we know about the accretion disk structure in CVs with low accretion rates from theoretical studies? Williams (1980) concludes that accretion disks in CVs develop optically thin outer regions for mass transfer rates below about $10^{-8} M_\odot yr^{-1}$ [15]. Tylenda (1981) confirmed this and added that an increase in the radius of the disk always increases the role of the thin region [16]. For $\alpha < 1$ the thin part of the disk is rather cool. The large part of the accretion disk is optical thin in the non-LTE regime and for $\alpha < 0.1$ the temperature can drop below 5000K[17]. Cannizzo & Wheeler (1984) studied the vertical structure of a steady-state, α-model thin accretion disk for an accreting object of $1M_\odot$[18]. They found that for low accretion rates the disk structure is optically thin. For $0.01 < \alpha < 1$ the solution of disk equations (1)-(3) ([18]) can be double-valued with high- ($\sim 5000K$) and low- ($\sim 2000K$) temperature branches. For $\alpha > 0.1$ a warm solution is possible in the inner region of the accretion disk, but material present at larger disk radii will be in a cold state with $T < 2000K$. Only the low temperature solution exists for $\alpha \approx 0.1$. When α decreases with temperature, this tendency to develop cold solutions in quiescence in enhanced. Until now models of disk emission spectra from such cool disks have not been calculated. The spectrum is nearly flat in the range 3000-10000Å for the model of the cool ($T = 5000K$, $\alpha = 0.03$) accretion disk[19].

Another important aspect of accretion disks in WZ Sge-type systems is the condition of their inner parts. In the standard model, this is usually optically thick and contributes to form a continuum of the disk's spectrum. However, in the case of the WZ-Sge-type system, various authors support the idea that the inner part of the disk need to be cleared up during quiescence in order to explain the long recurrent time for super-outbursts and the behaviors of the system between

super-outbursts in quiescence (see [20] and reference therein). It is not clearly understood why the inner part of the accretion disk is invisible. It can be caused by evaporation[21], the presence of a magnetic field of the primary WD[22] or an eclipsing by an optically thick spiral structure[23] in high-inclination systems, or be mostly a transparent in continuum.

Taken into consideration all the above we propose that the accretion disks in bounce-back systems are large (until 2:1 resonance radius), cool (about 2500K), optically thin with hot and thick two-spiral arm structures. There is probably a substantial cavity in the inner part.

4. The light curve simulation.

The double-humped with orbital period light curve in quiescence is a standing out feature of bounce-back candidates. The light curve model[24] of a CV system with a two-spiral armed thin accretion disk was adopted to bounce-back systems taking in the account positions of the bright structures in Doppler maps and a large size of the accretion disk. The small temperature gradient $T(r) \sim T(r_{in}) \times r^{-3/4}$ between the inner and outer edges of the disk and with $T \sim T(r) \times (1 + \beta \times z(r))$ in spiral arms (see Fig.4.) was assumed. We model such discs and generate light curves which successfully simulate the observed double-humped light curves of SDSS1238, SDSS0804, SDSS1610 and V 455 And in quiescence (Fig.5.).

5. Conclusion

We propose a likely model for a bounce-back system that explains their observed energy distributions, Doppler tomograms and double-humped light curves at quiescence. This model consists of ∼12000K massive ∼1M$_\odot$ white dwarf and a late type of the brown dwarf, and a large cool (∼2500K) optical thin accretion disk with a removed/invisible/transparent inner part of the disk and two-armed hot spirals in the outer part.

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